Semiconductor Optoelectronics
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Lecture – 41
Photoconductors

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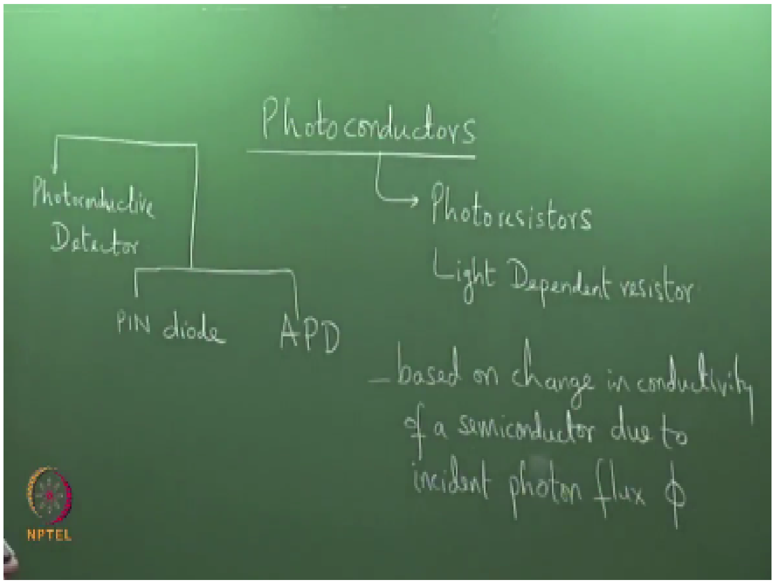

Photoconductors

→ Photoresistors

Light Dependent resistor

– based on change in conductivity of a semiconductor due to incident photon flux ϕ

Photoconductive Detector

PIN diode

APD

In the last 2 lectures, we discussed about the general characteristics of photo detectors and today, we will consider photoconductors. So, there are; as I indicated, there are 3 different important semiconductor detectors; one is the photoconductors or photoconductive; sometimes it is called photoconductive detector and photodiodes, in which we have 2 important categories that is PIN photodiode, so PIN diode and avalanche photodiode APV.

So, today we will discuss about photoconductive detector or simply photoconductors, sometimes people also call this as photo resistors, synonymous; photo resistors and when used in visible light applications many times we also call this as light dependent resistor, LDR; light dependent resistor. Basically, variations of the photoconductive detector, the basic principle of operation is as the name indicates, it is based on; it is based on change in conductivity.

Deduction of change in conductivity of a semiconductor due to incident photon flux phi, so based on the change in conductivity and hence the name photoconductive detector or photoconductors. It is one of the simplest detectors, which is basically, simply a piece of semiconductor of appropriate material and generally used in this configuration.

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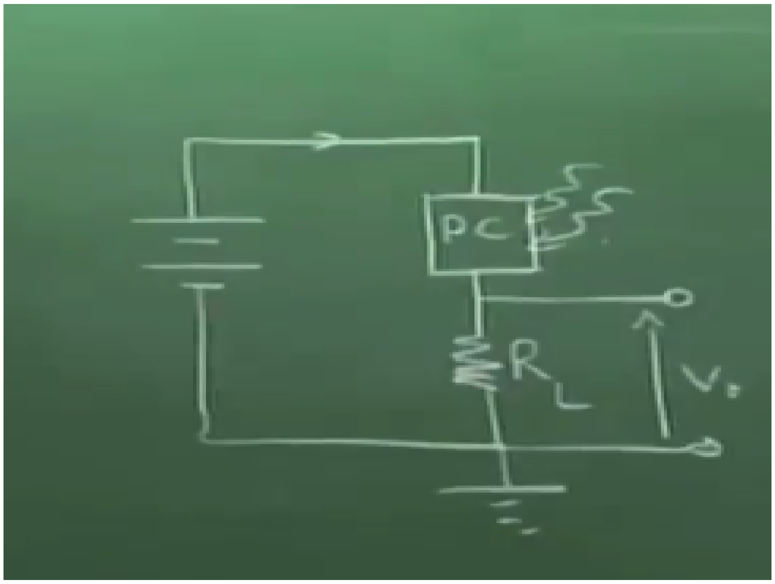

So, you have a supply here and here is the photoconductor, the different designs, so this is the photoconductor and is a load resistance, so the whole thing is grounded and here is the output, so vo. The output taken across a load resistance and this is the photoconductor, so incident; light is incident on the photoconductor; light is incident on the photoconductor with changes the conductivity of this element.

And therefore, hence the current through the device; so the current through the device changes and the current across the load resistance changes and therefore, you get an output, so, this is the basic configuration of use of a photoconductor or a photoconductive detector. This is one of the simplest detectors and it is a detector, which has a gain as we will see. So, let us see the responsivity of this detector; responsivity of the photoconductor.

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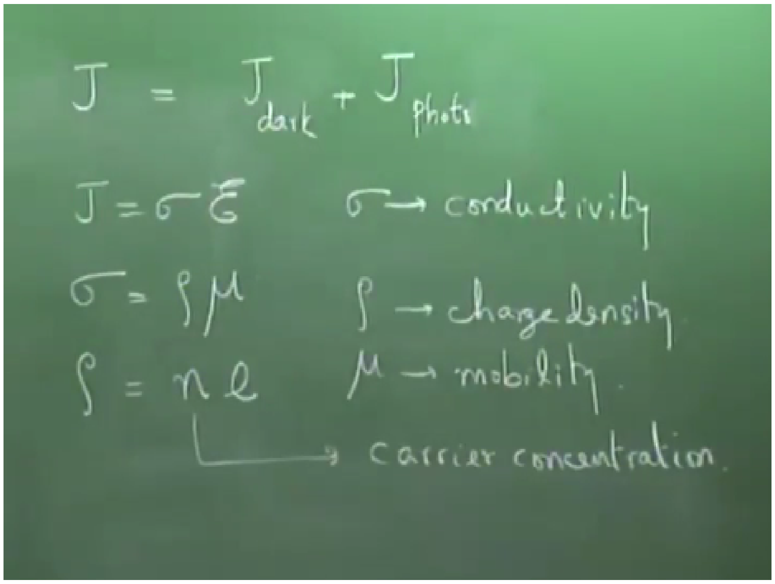

$J = J_{dark} + J_{photo}$

$J = \sigma \mathcal{E}$ $\sigma \rightarrow$ conductivity

$\sigma = \rho \mu$ $\rho \rightarrow$ chage density

$\rho = n e$ $\mu \rightarrow$ mobility

$n \rightarrow$ carrier concentration

So, how do we go about this? So, there is a change in conductivity therefore, if J is the current density; J is the current density through the current through the photoconductor, then J comprises of 2 components; one is J dark + J photon. J dark is the current density through the photoconductor, when there is no incident photon flux and J photon or J photo, it is not right photon; J photo is the current density, when there is a photon flux incident.

We know that J is = sigma * E, where; let me write the flower E because sigma E, where sigma E is the conductivity and sigma = rho * that is charge rho; charged density rho into sigma is conductivity, so this is rho * the mobility; sigma is = rho * Mu and rho is =; rho itself is =; if n is the number of carriers per unit volume, then n * e is the charged density; rho is the charge density and Mu is the mobility.

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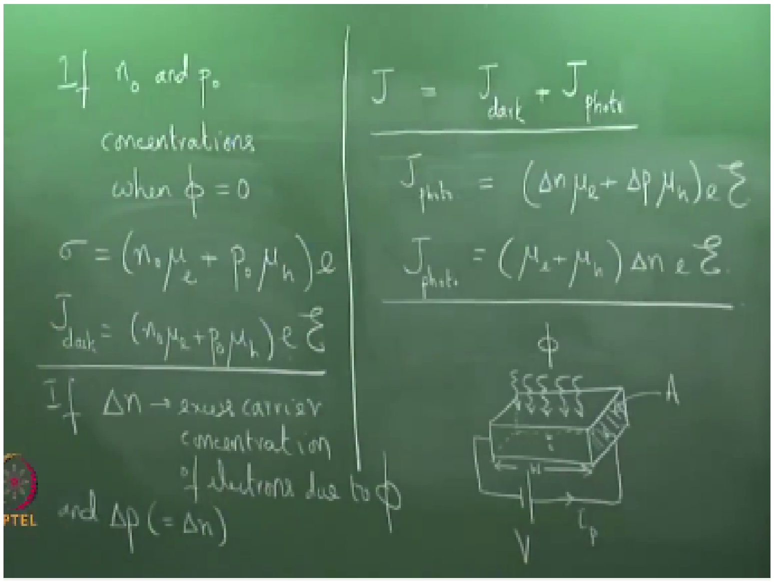

If n_0 and p_0 concentrations when $\phi = 0$

$$\sigma = (n_0 \mu_e + p_0 \mu_h) e$$

$$J_{dark} = (n_0 \mu_e + p_0 \mu_h) e \mathcal{E}$$

If $\Delta n \rightarrow$ excess carrier concentration of electrons due to ϕ and $\Delta p \, (= \Delta n)$

$$J = J_{dark} + J_{photo}$$

$$J_{ph} = (\Delta n \mu_e + \Delta p \mu_h) e \mathcal{E}$$

$$J_{photo} = (\mu_e + \mu_h) \Delta n \, e \mathcal{E}$$

And n is the carrier concentration, which means number of carriers per unit volume, n is the carrier concentration. So, if n0 and p0 are the carrier concentration of electrons and holes; dark carrier concentrations of electrons and holes, which means n0 and p0 are the concentrations, when phi is = 0. If n0 and p0 are the concentrations, when phi is = 0 that is dark carrier concentrations.

Then we have sigma is = rho, which is n0 *; this is for electrons, therefore Mu e + p0 + Mu h * e, so this is sigma. Sigma is = n0 Mu0 * this or J dark is = n0 Mu e + p0 Mu h for the holes into e; e is the electric field; applied electric field. So, this is the dark current density, we want to find out the total current density because from the current density then we can determine the current, so this is the dark current density.

Similarly, if delta n is the excess carrier concentration; is the excess carrier concentration of electrons due to phi; incident phi; due to phi. When a photon flux phi is incident on the photoconductor, it gives rise to; so, here is the photoconductor, so let me show the 3-D picture and we have applied a field here, the potential here, there is a photo current Ip, our interest is to determine Ip due to an incident photon flux phi.

And then estimate, then calculate what is the responsivity, so the photon flux is incident here, so this is phi; the photon flux. My objective is to estimate the responsivity; photon flux phi incident, let me consider a dimension W here; length of the photoconductor and this area of cross section here; area of cross section is A. If delta n is the excess carrier concentration of electrons due to phi and delta p is that of holes; excess carrier concentration of holes, which is = delta n.

Please see that PC that because it is the incident photon, which is creating electron hole pairs therefore, the excess carrier concentration delta n is = delta p, then J photo; I want to find out J photo, just like J dark that we have determined, so J photo is = delta n * Mu e + delta p * Mu h * e * E but delta n is = delta p and therefore, this is = Mu e + Mu h * delta n* e * E and therefore, the photo current; my final interest is to determine the photo current, okay.

Let me come back to it in a minute, so this is dark; J dark current density, when there is no photon flux; when there is an incident photon flux, this is the current density, delta n is the excess carrier concentration, e is the charge, Mu e and Mu h are the mobilities and E is the electric field. Electric field is if you apply a volt V here and W is a width, then V/W is the electric field, alright, okay.

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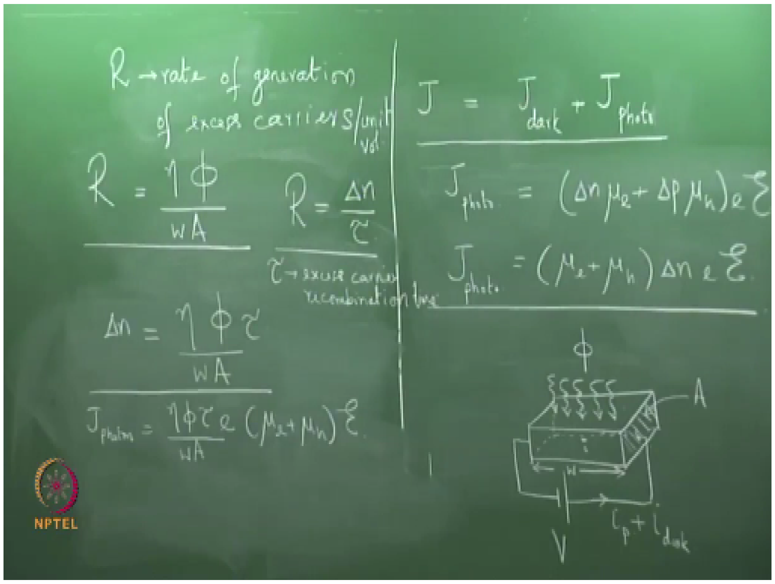

So, let us recall; oh, let me write; p0 Mu h * e * E, if R represents; if r is the rate of generation of carriers; rate of generation that is excess carriers; generation of excess carriers, then R per unit volume, then R is = eta quantum efficiency * photon flux, we call that; if phi is the photon flux, eta is the fraction, which will tell you the number of electron, the carrier flux which is generated, so eta/ w * A; w * A has come because per unit volume.

So, R is the rate of carrier generation per unit volume, then R is = eta phi/ w * A, where this is for volume but at steady state, the rate of carrier generation will be equal to the rate of recombination and we have already seen in an earlier lecture that R; the rate of recombination is given by delta n/ tau, where tau is the excess carrier recombination time, just before the electroluminescence, we had discussed before.

We discussed electroluminescence, we had shown that R; rate of recombination of carriers is = delta n/ tau, where tau is the excess carrier recombination time, steady state; the rate of recombination is equal to the rate of generation and therefore, let me remove this dark for a minute; for a while, so that from these 2, we can write delta n is = R * tau, which is eta * phi/ wA tau; delta n is = this.

Now, we are prime although, the total current density comprises of J dark + J photo, we are primarily interested in the photo generated current that is current generated due to the incident photon flux. Ideally, we would like J dark current to be 0, if there is a finite dark current, it will contribute to the noise power and hence in lowering the signal to noise ratio but ideally, we would like this to be 0.

But our primary interest is what is J photo and hence what is the photocurrent generated. I have written here Ip; photocurrent but actually this comprises also of I dark; Ip + I dark; the total current I, will actually in this case comprise of I dark, both Ip + I dark. However, our interest is to find out what is Ip. So, to get Ip, so delta n is = eta phi tau * this and if I substitute this J photo, so J photo that is photo generated current density is = eta phi tau/ wA that is delta n * e * Mu e + Mu h * E; Mu e * Mu h * e.

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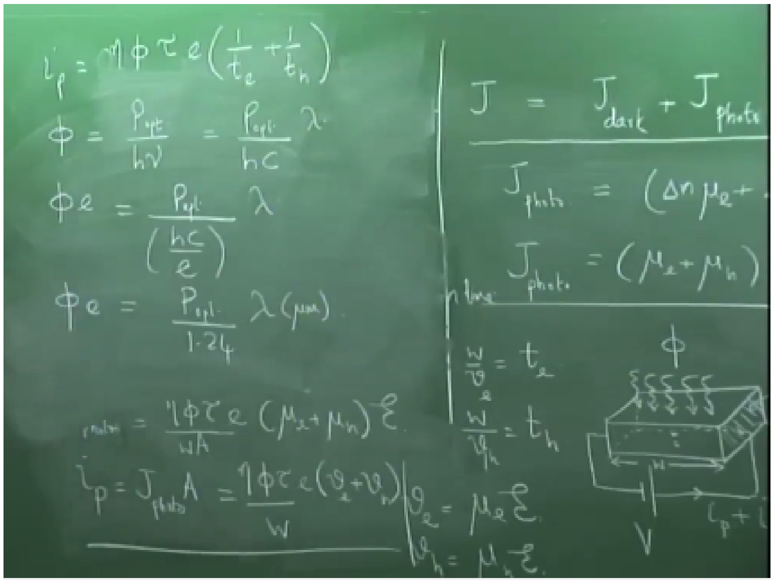

I have substituted from this expression here, for delta n here, I have substituted from here that is all, rest is the same. Now, A * J is the photocurrent Ip, therefore Ip is = J photo; J photo * A, which is =; so, A has gone here, eta phi tau; now, Mu e * E. What is Mu e * E, if you recall, the velocity of carriers; ve is = Mu e * E and vh is = Mu h * E. If E is the electric field and Mu is the mobility, then velocity of carriers is given by this.

So, Mu e * E is simply ve, so this is = eta * phi, I do not want to jump any steps divided by w * e, let me keep e into ve + vh; ve + vh. So, this is Ip, I do not want to jump any steps, so that we do not miss anything otherwise, you can simplify this very rapidly, very quickly. So, Ip is =; now, please see that ve/w; w is the width, ve is the velocity with which the electrons travel and therefore, that represents time, so w/ve is the transit time of electrons.

So, w/ve; shall I write okay, let me write here, w/ve = transit time of electrons and similarly w/vh is the transit time of holes; w/vh = transit time of holes, so this is essentially nothing but 1/ te + 1/th, so let me again not jumped any steps and write repeat again; phi tau/ w; oh, w is gone, into e * 1 /te + 1/th, phi s incident photon flux. So, if p0 is the optical power, which is incident, then p0 phi h Nu is the photon flux, this is power that is energy incident per unit time.

And divided by energy of one photon gives you number of photons incident per unit time that is the photon flux phi, so this is = P opt/ h C/ lambda here; h C/ lambda or I can take this lambda R and I write this as lambda. Now, phi * e; phi e here; phi e is = P opt/ h C/ e * lambda. If you substitute C in micrometres, lambda should be substituted in micrometres, then this number is 1.24, we have done many times this one.

So, this is = P opt/ 1.24, you can substitute constant 6.6 * 10 power -34, this is in microns, therefore it is 3 * 10 power 14 now; 13 * 10 power 8 meters or 3 * 10 power 14 and this is 1.6 * 10 power -19 will give you simply 1.24; 1.24 * lambda; lambda to be remembered that this is to be substituted in microns. So, phi * e is this, so I want to substitute for phi * e this one, here. So, this is let me remove these, now we do not need this.

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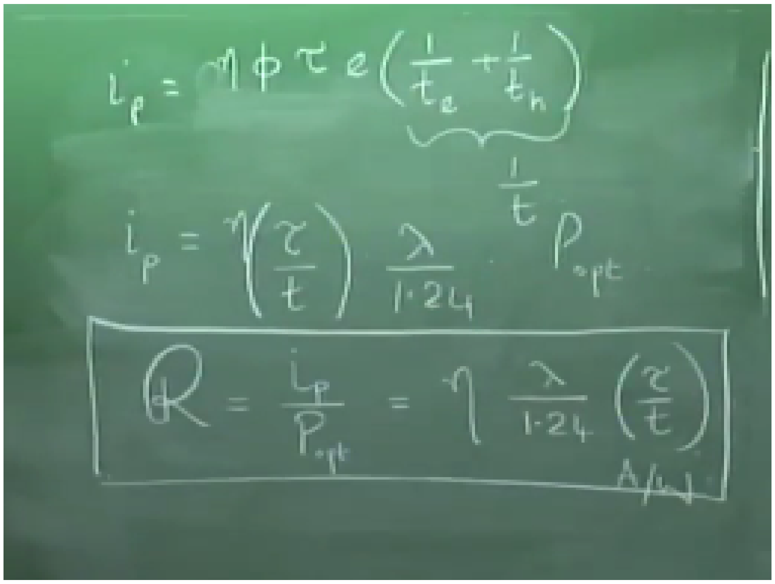

$$i_p = \eta \phi \tau e \underbrace{\left(\frac{1}{t_e} + \frac{1}{t_h}\right)}_{\frac{1}{t}}$$

$$i_p = \eta \left(\frac{\tau}{t}\right) \frac{\lambda}{1.24} P_{opt}$$

$$\boxed{R = \frac{i_p}{P_{opt}} = \eta \frac{\lambda}{1.24} \left(\frac{\tau}{t}\right) \quad A/W}$$

So, phi * e is this one, this term, I want to call 1/ t, which is 1/te + 1/th and therefore, we can write Ip is = eta * tau/ t here, this 1/t tau/t * lambda/ 1.24 * P opt; lambda/ 1.24 * P opt, you know why I have written return like this is my final interest there it is my expression for responsivity is = Ip/ P optical power incident, which is = eta * lambda/ 1.24 * tau/t. Responsivity Ip/P opt, so the units are amperes per watt.

So, I have; from basic relations, basic concepts we have derived a simple expression for the responsivity of the photo conductor; responsibility of photo conductor. It is not a difficult derivation at all, it is very simple one, without jumping any steps I have shown you that we get an expression for the responsivity of the photo conductor; responsivity of the photo conductor, R is =;

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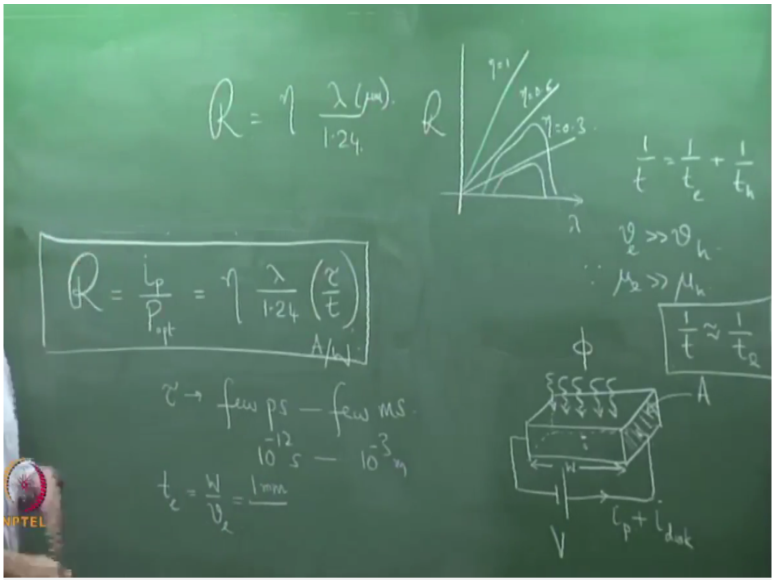

When we discuss the general characteristics a couple of lectures before, when we discussed the general characteristics of detectors, we had an expression for responsivity; R which was = eta * lambda/ 1.24. Hope you recall the graphs that we had plotted, if eta was not changing, eta was constant then we do this, so responsivity R verses lambda, for different values of eta; eta = 1, eta = 0.6, eta = 0.3.

And then in the following lecture, we discussed the dependence of eta on wavelength and then we got responses like this because eta; there was a long wavelength cut off and also it was decreasing down to 0 near short wavelengths. Now, we see that there is an additional term tau/t. In all these considerations, we did not take transit time of carriers into account. Now, we in this analysis, we have taken the transit time w/ve.

So, because of the transit time, now we have a factor tau/t; tau is the carrier recombination time, typically this could be from few picoseconds to few millisecond, depending on the material and structure, design, it could be few picoseconds to a few milliseconds, which means of the order of 10 power -12 seconds to 10 power -3 seconds. Tau; carrier recombination time, transit time t, okay, let us look at 1/t.

Here, 1/t is = 1/te + 1/th, in general, ve is much > th because mobility Mu e is much > Mu h. In detectors like gallium arsenide or Indium arsenide; if you take Indium arsenide, it is Mu e is about 33,000, whereas Mu h is few 100, so you can see that the Mu e is much > Mu h in general but there are many materials where even Mu e could be < Mu h but most of the detector materials which we use, they have Mu e much > Mu h or at least >.

Therefore, ve > vh and therefore te is much smaller compared to th, therefore 1/t is much greater compared to 1/th. In other words, we can write that 1/t is approximately = 1/te because th is much larger compared to te, transit time of holes that this 1/th becomes much smaller compared to 1/te and therefore, 1/t is approximately = 1/te. We could retain 1/t itself, there is no problem but if we take this then we need to discuss about the transit time of electrons only.

Otherwise, it does not matter, there is no; so te; transit time of electrons is = w/ve and w; if I take typically, w is = let us say 1 mm, the width here is about 1 mm or few millimetres, the semiconductor material; the dimension of the semiconductor if; and ve, if I apply an electric field so that ve is approaching saturation velocity, we discussed about saturation velocity, which is of the order of 10 to the power of 7 centimetres per second.

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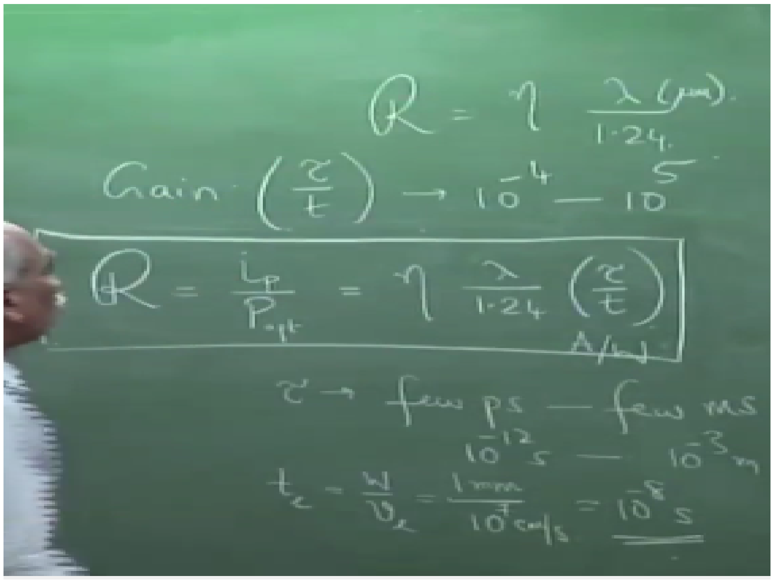

$$\mathcal{R} = \eta \frac{\lambda(\mu m)}{1.24}$$

$$\text{Gain}\left(\frac{\tau}{t}\right) \rightarrow 10^{-4} — 10^{5}$$

$$\boxed{\mathcal{R} = \frac{i_p}{P_{opt}} = \eta \frac{\lambda}{1.24}\left(\frac{\tau}{t}\right)\ \text{A/W}}$$

$$\tau \rightarrow \text{few ps} — \text{few ms}$$

$$10^{-12}\,s — 10^{-3}\,m$$

$$t_e = \frac{w}{v_e} = \frac{1\,mm}{10^{7}\,cm/s} = \underline{\underline{10^{-8}\,s}}$$

Then this will be nearly equal 10 power -8 second, the transit time of electrons is approximately 10 power -8 per seconds, we are putting some numbers to get a feel for what kind of; what kind of factor; this factor is >1, it means responsivity has a gain, there is a gain factor and indeed photoconductors provide gain because of this. Now, if I use 10 power -8, then we can have gain means tau/t, so if you go to this end, it is 10 power -12/ 10 power -8, which is 10 power -4.

This is ranging from 10 power -4, if you come to this end, it is 10 power 5, this factor is as high as 10 power 5, so you see that in photoconductors, there is a gain possible, the responsivity can be very high, I will show you a typical plot and the number for responsivity is 10 power 2, 10 power 3, 10 power 4, very high responsivity that is because of this. Of course, there is a high responsivity or high gain comes at a cost.

You will see that the speed is going to be much less compared to PIN diodes but there is gain which is available in this. How does this gain come? We know about gain coming from a avalanche multiplication like in APD's, there is carrier multiplication taking place that is an accelerated electron knocking out more electrons and hence there is a large avalanche multiplication. There is no avalanche multiplication in this case, in the case of photo conductors.

But there is gain, when the gain could be very significant, so you could have this factor tau/tau in this range. So, if you make the transit time te; if the carrier recombination time is very small, then it could be here, otherwise you can have a large gain possible. Now how does this gain come? Let us briefly discuss the physical origin of this, where is the gain coming.

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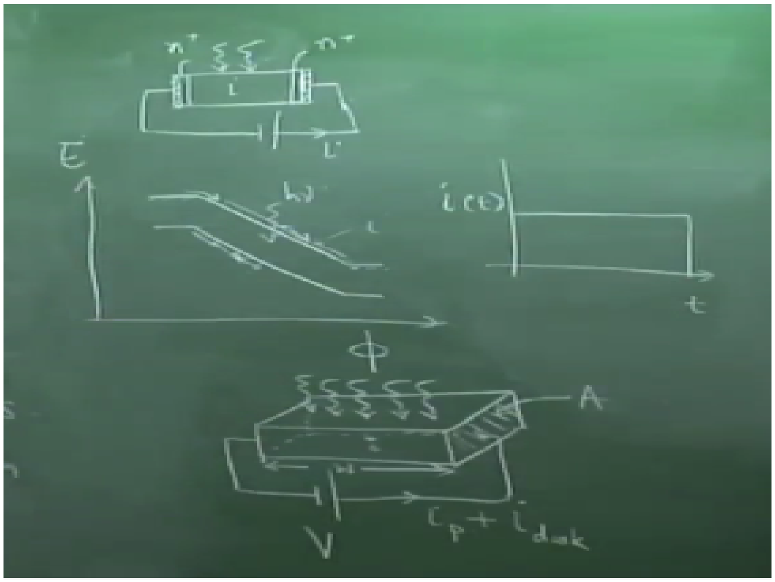

Typically it is a; the photoconductor is typically like this, they normally use a metal contact here let us say metal and therefore for ohmic contact, you normally use n+ here and then an intrinsic medium and n+, it is only for contacts sake, this is metal, so this n+ and intrinsic, so the carriers are photon flux is incident here, there are better designs but I am just explaining that there is; so, if you draw the band diagram of this, so you n +, which means the electron thermi level is here.

And then, this is the intrinsic region, then we have like this, what I drawn is the familiar energy band diagram of this, so this is the I region intrinsic. So, I have applied positive to this end, therefore the potential here is decreased, so what is plotted is E verses the distance; so E verses the distance. Incident photon let us say 1 photon is incident here to this region h Nu. So, it creates a hole and an electron in the conduction band and hole in the balance band.

The hole starts moving up, it is like air bubble, so starts going up the slope and this is like water droplets, so it starts going down. These are the 2 ends where it is collected. Now, because the velocity of electrons is very high compared to this, electron goes rapidly and reaches this end. When electron reaches this end, so when electron is moving this side and hole is moving this side, there is a current in the external circuit.

There is a current I here in the external circuit because of charge carriers moving, we have discussed this in the last class before impulse response by Ramo's theorem, it tells you that there is a current, which is in the external circuit. When the electron is collected here, then to maintain charge neutrality, this second electron is released from here, from this contact because there is only one hole, which is moving.

Hole is still, before the hole has come here, the electron has been collected, so a second electron is released because this is once it is collected, it is gone into the conductor. So, this electron again starts going, hole is further proceeding and it is collected here, next electron is released, this is further proceeding. So, till either the electron hole recombines in the medium or both electrons and holes are collected by the contact electrode at the ends, this process takes place.

Please see, there was only one photon which was incident, there is a carrier pair, which was generated but there were so many electrons were transiting through this, by the time one hole was travelling up and this is why, there is a persistent current in the external circuit for a long time. Although, you had just put 1 photon, which has made 1 carrier, so the current flows for a longer period in the external circuit and that is response.

We have discussed with the 1 photon, if you have larger number of photon, you can imagine that there is a big current in the external circuit although, there was just a burst, so this is responsible for this and that comes because of the large carrier recombination time, which means these electron and hole are not recombining inside the semiconductor for a long time. The moment they recombine, if this was very small.

For example, this is smaller than this then even before it reaches here, it would have recombined, which means the current will persist only for a small duration and therefore it is the carrier recombination time, which will; but we know that because it takes a long time to go here, the impulse response will be spread, even so, now the impulse response would look like so it is continuously coming for a long time.

So, this is time t, and this is current i of t for a long time because the carrier recombination time is very large. So, what have we compromise? The speed, to get gain, what you have compromised is speed because the impulse response is now spread, the transit time spread is much larger. So, photoconductors can provide gain but at the cost of speed. You can indeed show that the gain bandwidth product remains a constant.

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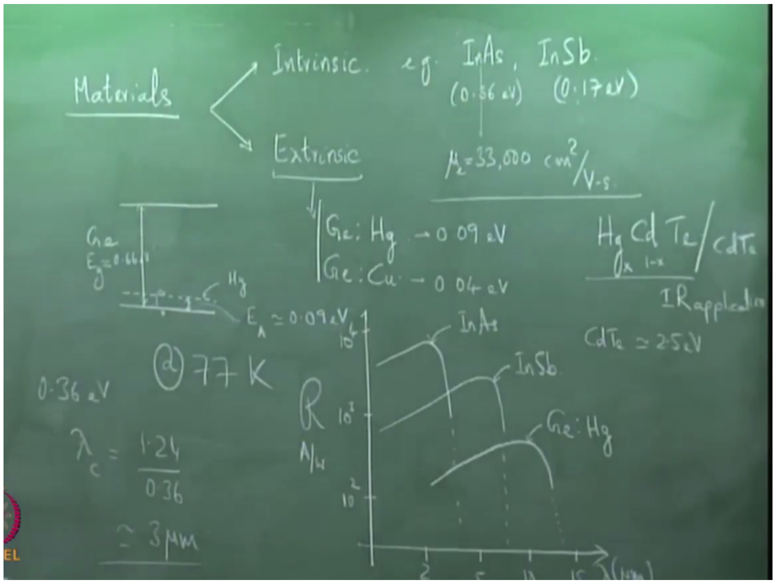

Now, let us come to materials, which are use so long, I did not discuss about materials, so materials; generally, photoconductors are used to; generally, these are used to detect long wavelength materials and therefore there are 2 types or 2 kinds of materials which are used, they are, intrinsic and extrinsic. As you know intrinsic normally refer to pure semiconductors and extrinsic refers to doped semiconductors.

And the same thing is true here that we have intrinsic semiconductors such as widely used semiconductors. For example, Indium arsenide and Indium antimonide, this has a band gap EG of 0.36 ev and this is 0.17 indium antimonide. These 2 materials are widely used because as I also mention they are very large mobility; electron mobility in Indium arsenide is about 33,000 centimetres square per volt second. Similarly, Indium antimonide is about 8000 or 8500 centimetre square per volt second, very large mobility.

And therefore, very small te and therefore, you can get relatively large gain and extrinsic; extrinsic semiconductors, the widely used semiconductor is germanium doped; mercury doped germanium or copper doped germanium. Typically, the activation energy here we are referring to this, so let me draw this, what we are showing. This is germanium; band gap of germanium, Ge, Eg is approximately 0.66 ev.

And because of mercury doping, there is a activation energy here, there is an acceptor level, so these are mercury level Hg doping and this activation energy; energy gap here is approximately; EA is.0.09 eV and for copper, it is even smaller, I think about 0.04. So, for this it is approximately 0.04 eV and here it is 0.09 eV. So, obviously if you want to use these detectors, they have to be cooled otherwise, thermal agitation at room temperature; acceptor atoms will all accept electrons there and there will be plenty of holes here.

And therefore, the dark currently will be very large. So, usually you should cool these detectors at 77 K, normally, these are cooled at liquid nitrogen temperature while using, so the incident photon energy, if it corresponds to this activation energy, then it will respond; in the sense, if the electron will go here to the acceptor level living behind a hole and the hole will cause conductivity.

So, the conductivity is due to holes created here or just like in a p -type material, you have acceptor levels, which accept. So, the widely used extrinsic materials are germanium doped mercury and; people also use for infrared application, a material which is also widely used is mercury cadmium telluride, so Hg mercury cadmium telluride, so, it is Hg x 1 – x mercury cadmium telluride. Cadmium Telluride, so this is mainly for IR applications, although Cadmium Telluride

Because this is mercury cadmium telluride is lattice matched to cadmium telluride, so you can go different combinations of the Hg Cadmium telluride on cadmium telluride and Cadmium telluride has a band gap of about 2.5 eV, which is very much in the visible but Mercury telluride has a band gap, which is very close to 0, so you can by varying x, you can cover the entire IR range, from visible to IR, it is possible.

This is an important material which is used for IR applications, a ternary compound mercury Cadmium telluride and cadmium telluride. So, if I plot typical responsivity curves for these, it looks like this. So, let me plot the responsivity, so responsivity, amperes per watt, typically 10 to the power of 2, 10 power 3, 10 power 4, and wavelengths are of course large, you can calculate. For example, for this 0.36 eV, what is the; so, 0.36 eV, so which means 1.24 Eg, so lambda cut off, so lambda c is = 1.24/0.36.

How much is that? Approximately 3; approximately 3 micron, so, lambda cut off in; so approximately 3 micrometers and similarly, if you go for this, it will be about; so, let me plot, so 2, 5, 10, 15, this is lambda in micro meters. So, the responsivity, typically looks like this, so this is for Indium arsenide, this is for Indium antimonide and this one, I have plotted for Hg germanium; germanium doped Hg, in other way to be written.

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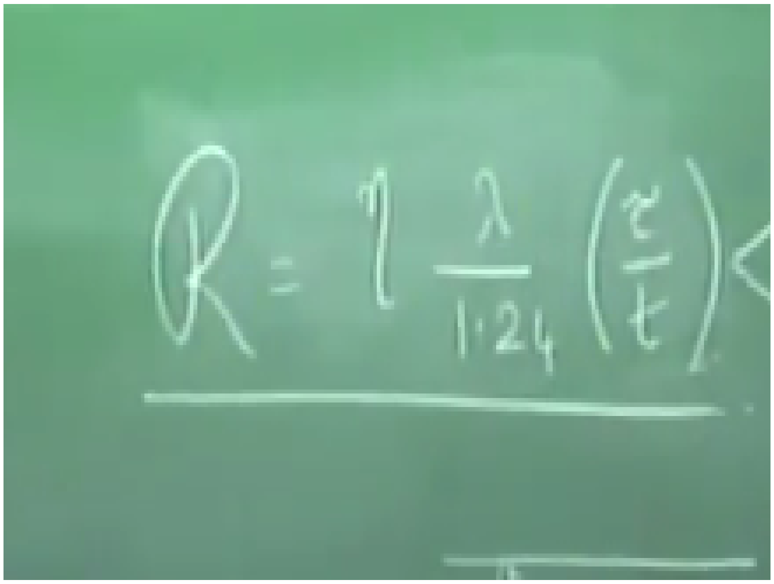

$$R = \eta \frac{\lambda}{1.24}\left(\frac{\tau}{t}\right)$$

So, typical responsivity, you can see initially the linear behaviour because it is proportional to lambda, if you recall the responsivity for R is = eta * lambda/1.24 * tau/t. Why Indium arsenide has a very high responsivity? You can see is mobility is very high, therefore this t is very small, so that that is why the responsivity is very high. When we see for normal PI and photodiodes, you will see that the responsivity is 0.5, 1, 1.2 that is the kind of numbers but here, we have very large numbers.

So, Indium arsenide; because it has a very large mobility, has a very high responsivity. The only thing is these are much slower detectors one and I will come to the second disadvantage also. So, the initial portion you can see this linear variation is primarily because of this linear dependence on wavelength and then this drop, we know because of long wavelength cut off because the band gap of the material.

So, further long wavelength, the band gap of the material is larger than the photon energy and therefore, there is no absorption, no carrier generation. Is this alright? So, we come to finally one high speed; high speed design which is widely used photoconductor. One of the; as we discuss one of the major problem is carrier transit time and recombination time. So, recombination time can be minimised, can be reduced by using pure materials with minimum defects.

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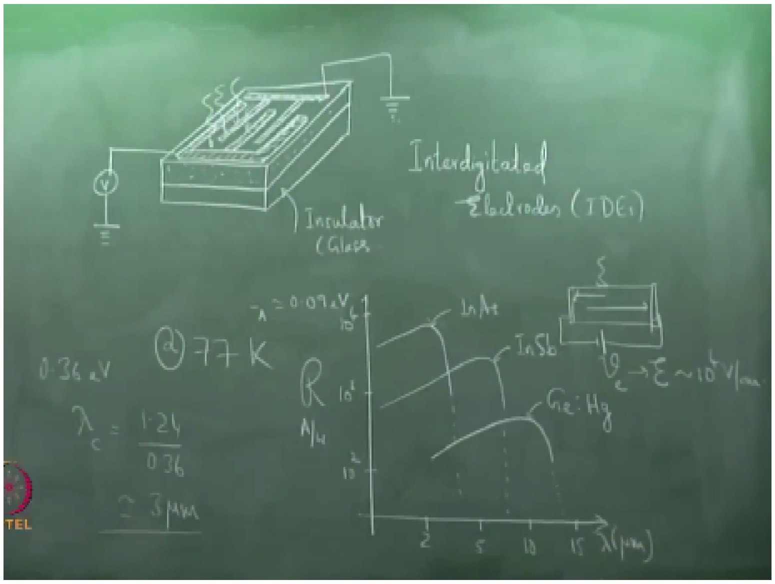

And transit time can be minimised by using inter digitated transducers, so the normal design, we have had these photoconductors are used, they use IDE’s; inter digitated electrodes, so let me show you. So, this is the photoconductor and this is grown; a film of photoconductor grown on an insulator; typically, an insulator, usually glass; transparent glass and this is a photoconductor, this layer is the semiconductor and on this, they make IDE's that is inter digitated electrodes, so let me show you, okay, let me draw it, it will become clear as soon as I finished the drawing.

These are monolithic electrodes, what I have drawn here is metal electrode, which are deposited on top by lithography, so this electrode here for example, is collected to a supplier and this is other electrode, which is grounded. So, there is an electric field between these, this finger like structure, so it is inter digitated. They are called inter digitated IDE; inter digitated electrodes. The advantage is that this reduces the transit time, so photons are incident here that is light is incident.

The advantage is the generated carriers will find a electrode very close, it does not have to travel as I have had shown in the diagram earlier that photons incident, the electrons and holes have to travel a long distance, so this increases the transit time. So, to minimise the transit time and hence to increase the speed, one uses IDE's. The second advantage is if you apply an electric field at the end to get ne, please remember to have a highly saturation velocity ve, we need electric fields of the order of 10 to the power of 4 to the 10 to the power of 5 volt per centimetre.

We want to have high speed, so ve should be saturation velocity as discussed in the last lecture; you need very high electric field. If you; if this separation is large let us say several millimetres, then the field required will also be the; the voltage required; the v have to be to be applied is also very large but here they are close by; the separation is very small, so even by applying very small voltages like that TTL logic, +5 volts, you can get very large electric field between them

Because the separation is small that is the advantage of using IDE's in all high speed devices. These are also widely used in SAW devices, surface acoustic wave devices, where IDE's are used to increase the speed. So, high speed design, one last point before we come to the IV characteristics of the photo detector. So in all; for the design engineer, the IV characteristic is very important; one is the responsivity, whenever you want to use a photo detector or a source, you have to know the responsivity and second is the IV characteristics.

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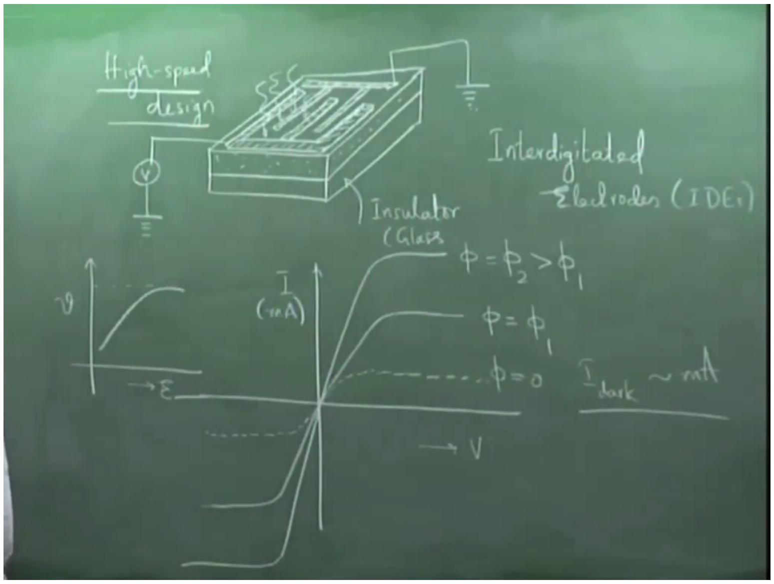

So, how do you think the IV characteristic would look like? It is a simple piece of semiconductor and you have applied a current, so the IV characteristic of the photoconductor looks like this. So, this is what I have shown by dashed line is when; okay let me draw completely, so what I am plotting is the I, the photocurrent IP verse the applied voltage v. So, you have; so this is with phi = 0, phi = phi 1 and phi = phi 2, which is > phi 1.

The incident photon flux but what you see is it symmetric because it is simply a piece of semiconductor, it does not matter whether you apply from this side or that side, it is not a diode and therefore, there are no rectifying behaviour, so it is simply same. The current here is in milli amperes including the dark current, please see the dark current; I dark is also of the order of miili amperes, whereas in the case of a photodiode, there is a reversed biased photo diode, the dark current is of the order of micro amperes.

So, the major disadvantage of photoconductors is the dark current; large dark current. This a major disadvantage of photoconductors. In any high speed application or where you need very good signal to noise ratio but the real advantage of photoconductors is; if you want to detect long wavelength; IR wavelengths for example then photoconductor or the detectors which are used. So, this is the IV characteristic with one disadvantage is, I dark.

What we have shown is for different photon fluxes, you can see initially it varies linearly because you are applying velocity voltage and therefore, the full electric field is increasing but once the saturation velocity has reached, there is no more change in current because current is proportional to the mobility into the total number of carriers that you have and therefore as electrical field increases, the velocity increases.

Therefore, initially it is behaving linearly but afterwards as you know that one reaches saturation velocity, so this is electric field E versus velocity V, so this is the saturation velocity and therefore, there no more carriers, which are remaining to be swept, so there is a average velocity where it has saturated and therefore the current saturates to that value. So, I think there we have covered almost all aspects, which are relevant to photoconductor, one type of detector, which is used for common applications.

But normally not used for high speed applications, all high speed applications, we use either PIN diodes or APD’s. The highest speed; there are various designs of PIN diodes and the highest speed that we now have, there are detectors, which detects 100’s of gigahertz bandwidth and they are based on PIN detectors; PIN diodes or their variance. So, we will stop here, is there any specific question? any specific question? So, we will stop here.